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Monterey, California

PRELIMINARY CRUISE REPORT OF USNS BARTLETT

TO THE GREENLAND SEA IN SEPTEMBER 1989

Robert H. Bourke, Robert F. Blythe, and
Robert G. Paquette

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Interim Report for Period August 1989-November 1989

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page

List of Tables

List of Figures

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Robert H. Bourke, Robert F. Blythe, and Robert G. Paquette

ABSTRACT

As a component of the Greenland Sea Project, a hydrographic cruise was conducted on board the USNS BARTLETT during September 1989 in the southern Greenland Sea to characterize the water mass structure and circulation features of the Jan Mayen Current (JMC). A total of 48 high-quality CTD stations were occuppied to depths of 1000 m; five stations extended to 3000 m or more. Five north-south tending transects permitted tracking of the JMC by its low temperature (< $0^{\circ}C$), low salinity core. The JMC could also be well defined from its intermediate water properties. Deep stations made in the trough of the Jan Mayen Fracture Zone suggest that the interchange of deep and bottom water from the Greenland and Norwegian Seas via this trough is a slow diffusive process and not an active advective feature as previously thought.

I. INTRODUCTION

In support of the multinational Greenland Sea Project (GSP) a hydrographic cruise was conducted on board USNS BARTLETT (T-AGOR-13) during the month of September 1989 by personnel from the Naval Postgraduate School (NPS), Scripps Institution of Oceanography, and the University of Paris. The cruise statistics are presented in Table 1. The GSP is a five year effort to monitor the water mass and current structure of the Greenland Sea on a nearly continuous basis. Such monitoring is necessary as the Greenland Sea acts as the gateway between the cold, fresh polar waters of the Arctic Ocean and the warm, salty waters of the Atlantic Ocean. Climatological changes in one basin are transmitted to the other through the Greenland Sea.

The Greenland Sea is dominated by a broad cyclonic circulation. Polar Water (PW) exiting the Arctic basin flows southward along the east coast of Greenland. Between 72°N and 74°N a branch of the PW flows eastward, presumably guided by bathymetric fracture zones, to eventually join with the northward flowing Norwegian-Atlantic Current near the mid-ocean ridge system. This eastward flowing branch, termed the Jan Mayen Current (JMC), is a major source of ice and fresh water to the circulation in the Greenland Basin.

Table 1. BARTLETT Cruise Statistics

Vessel: USNS BARTLETT (T-AGOR-13)

Depart: Tromso, Norway 6 September 1989

Return: Trondheim, Norway 23 September 1989

Miles travelled: 2784 n mi

Number of shallow stations (0 - 1000 m): 43

Number of deep stations (3000 m): 5
Stations 2,11,21,40, and 48

Total stations: 48

Instrumentation: Neil Brown MK III CTD with 12-place rosette sampler with 2 liter Niskin bottles and low temperature range (-2°C to +2°C) reversing thermometers

Nominal bottle depths:
Shallow stations: 1000, 900, 800, 700, 600, 500, 400, 300, 200, 100, 75, and 10 m
Deep stations: 3000, 2800, 2600, 2400, 2200, 2000, 1800, 1600, 1400, 1100, 700, and 300 m
Thermometers usually on bottles at 1000, 800, and 75 m depth

Scientific Party:
Professor Robert H. Bourke, Chief Scientist, NPS
Professor Jean-Claude Gascard, NPS and University of Paris
LT Robert F. Blythe USN, NPS student
Ms. Marla D. Stone, NPS technician
Mr. Vernon N. Anderson, NPS technician
Mr. David A. Muus, ODF/SIO research associate
Mr. Julien J. Gascard, University of Paris

II. OBJECTIVES

Other than surveys conducted throughout the summer and winter of 1958 as part of the International Geophysical Year (IGY) (Dietrich, 1969), few observations have been made of the JMC, the southern limb of the Greenland Sea gyre. The purpose of the cruise was to measure and quantify specific features of this current such as its speed, volume flow rate, areal extent, water properties, and fresh water contribution. Data were collected to address the following specific objectives:

1. Determine the latitudinal extent of the eastward flow, i. e., establish the northern and southern boundaries of the JMC as it departs from the East Greenland Current (EGC),
2. Establish its relation to the bathymetric fracture zones which are presumed to steer it,
3. Determine the eastward extent of the JMC,
4. Determine the frontal characteristics of the northern and southern boundaries of the JMC, and
5. Determine the flow rate of the JMC based on geostrophic calculations and ice drift rates.

In addition to the hydrographic survey, there were two ancillary objectives relating to the GSP.

1. Install four autonomous listening arrays (ALSs) on shallow (<2000 m) promontories. These arrays are designed to track the motion of SOFAR floats. The floats, nominally drifting at 100 m or 1000 m depth,

were deployed in the Arctic Ocean north of Svalbard last summer (1988) as part of the CEAREX Project.

2. Make deep water CTD casts to re-affirm the theory of formation of Norwegian Sea Deep Water (NSDW). The prevalant theory (Swift and Kolterman, 1988) is that NSDW is derived from a mixture of Eurasian Basin Deep Water (EBDW) and Greenland Sea Deep Water (GSDW). The product of this mixture, "new" NSDW, is thought to enter the Norwegian Sea principally via a trough in the deep fracture zone just north of Jan Mayen Island.

III. CRUISE PLAN

In order to achieve the objectives outlined above a series of north-south tending hydrographic lines were laid out from 72°N to 75°N which were expected to pass through the anticipated course of the Jan Mayen Current. The positions of these hydrographic lines were based on a CTD station census plan produced by the GSP Steering Committee to aid GSP participants in setting up their cruise plans (Figure 1). The desired goal of the census plan is to achieve as many repeat samplings of the water column as possible during the five years of the project in order to establish seasonal and interannual fluctuation statistics. Also shown on this chart is the location of an intercalibration site (71°N, 4°E) near the center of the Lofoten Basin whose purpose is to determine the uniformity of deep water

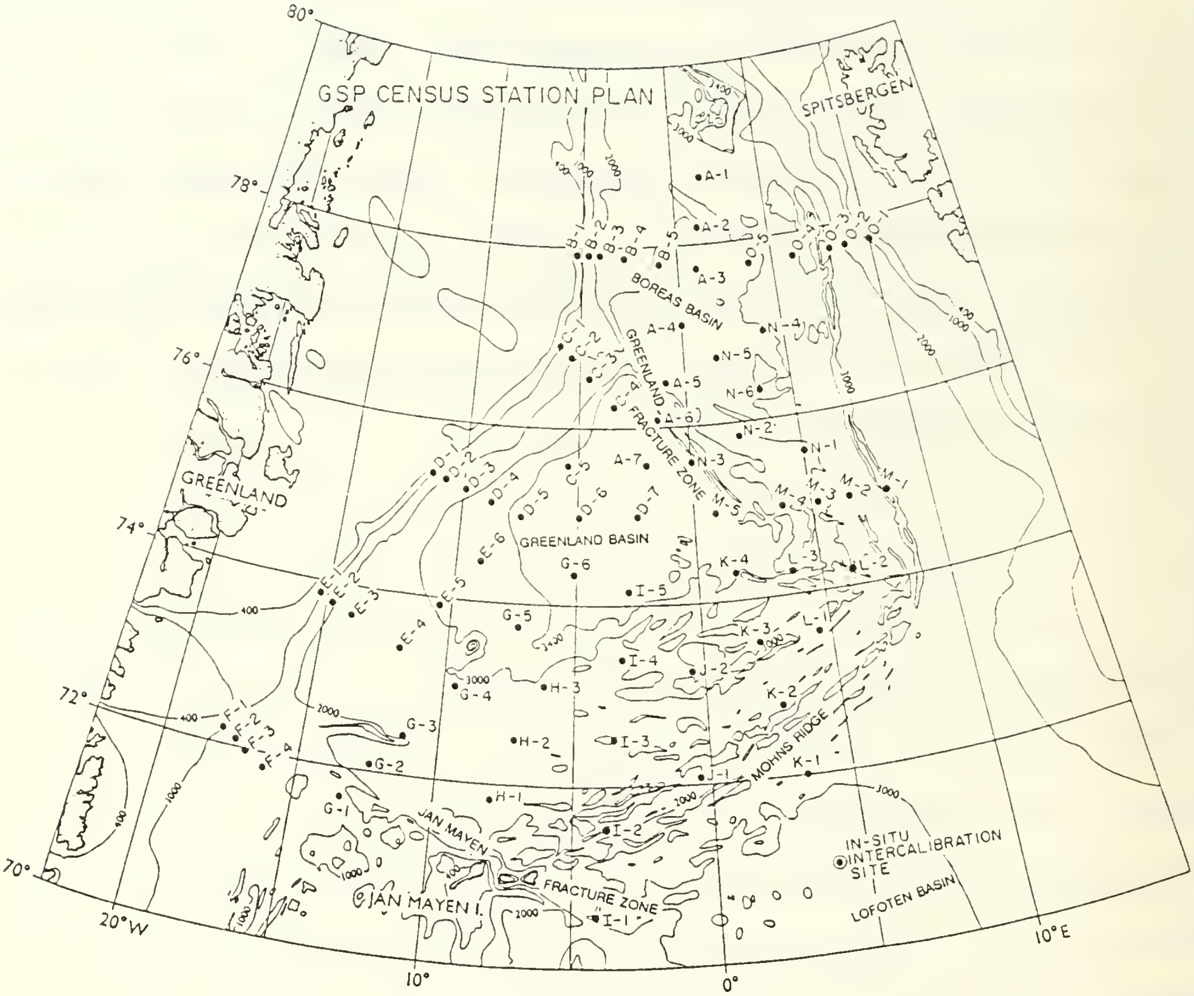

Figure 1. Hydrographic sampling plan for the Greenland Sea Project. The intercalibration site in the Lofoten Basin is to be sampled by all participants in the GSP to aid in intercomparison of data. Bottom contours (meters) and major bathymetric features are shown.

measurements amoung GSP investigators.

The position of the actual CTD stations and cruise track are shown in Figure 2 and listed in Table 2. As can be seen, our stations are more closely spaced (35 to 50 km apart), often with two or more stations located between a pair of GSP primary stations. To optimize our station plan within the time constraints of the cruise, it was necessary to limit most of the CTD observations to 1000 m depth. Water samples were collected at 12 depths at approximately 100 m intervals for salinity and dissolved oxygen measurements. At appropriate locations deep water CTD casts to 3000 m (or the sea bottom) were made to assess the nature of the deep water, their locations shown in Figure 2 with solid circles. Deep water samples were nominally collected at 200 m intervals over the 1000 m to 3000 m depth range. See Table 1 for specific details.

IV. INSTRUMENT CALIBRATION

A basic philosophy of the GSP was calibration of instruments from all participants at a common location. This was to insure that data could be interchanged among all participants with no instrument biases. To achieve this goal all CTD's were calibrated, both statically and dynamically, at the Ocean Data Facility of Scripps Institution of Oceanography (ODF/SIO). The NPS four-sensor Neil Brown MK III CTD was shipped to the ODF for

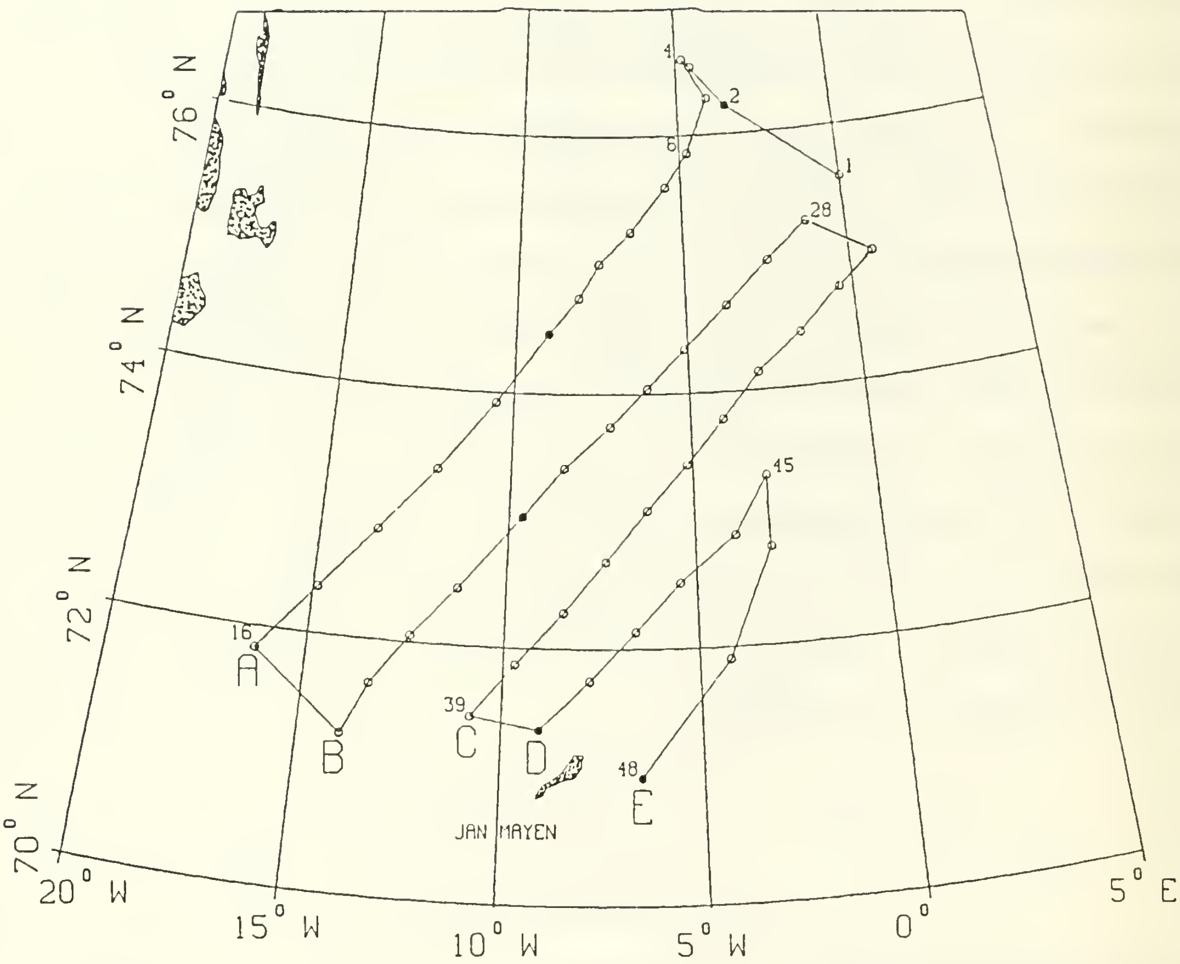

Figure 2. Trackline and location of CTD stations during the BARTLETT 89 cruise to the Greenland Sea. CTD stations extending to near bottom (3000 m) are denoted by solid circles. The location of vertical cross-sections are shown as Transects A through E.

Table 2. CTD Station Data

Sta	Lat (deg-min)	Long (deg-min)	Date	Hour	Bottom depth (m)
1	75-35.3N	000-00.0E	9	17.5	3750
2*	76-13.7N	003-27.7W	10	04.8	3580
3	76-32.5N	004-32.6W	10	11.6	2690
4	76-36.1N	004-47.1W	10	13.9	2290
5	76-17.5N	004-03.8W	10	18.3	3510
6	75-51.6N	004-46.8W	11	01.5	3410
7	75-35.8N	005-30.5W	11	05.6	3410
8	75-15.4N	006-38.0W	11	10.4	3440
9	75-00.7N	007-36.3W	11	14.1	3360
10	74-44.9N	008-12.1W	11	17.3	3320
11*	74-28.1N	009-03.1W	11	20.9	3230
12	73-55.3N	010-30.5W	12	05.5	3010
13	73-22.7N	012-01.9W	12	11.0	2740
14	72-52.4N	013-28.4W	12	16.4	2450
15	72-22.2N	014-52.0W	12	21.8	1950
16	71-49.9N	016-15.7W	13	03.1	1120
17	71-14.4N	013-56.7W	13	10.1	930
18	71-39.4N	013-20.9W	13	14.5	1740
19	72-03.3N	012-24.7W	13	19.0	2350
20	72-27.1N	011-16.4W	14	02.8	490
21*	73-02.1N	009-38.5W	14	13.4	2880
22	73-25.1N	008-33.1W	14	21.0	2970
23	73-44.7N	007-17.4W	15	02.6	3240
24	74-02.4N	006-13.9W	15	06.4	3380
25	74-20.5N	005-06.5W	15	10.4	3460
26	74-40.6N	003-49.4W	15	14.8	3740
27	75-00.1N	002-30.6W	15	19.0	3640
28	75-16.4N	001-13.1W	15	22.9	3690
29	74-59.2N	000-42.7E	16	08.5	3710
30	74-44.6N	000-25.2W	16	12.1	3710
31	74-25.4N	001-42.3W	16	15.9	3640
32	74-08.4N	003-01.1W	16	19.8	3600
33	73-47.4N	004-06.3W	16	23.8	3690
34	73-26.7N	005-09.5W	17	04.0	3030
35	73-05.3N	006-17.0W	17	08.2	2600
36	72-41.1N	007-25.4W	17	12.5	2300
37	72-17.0N	008-30.0W	17	17.0	2520
38	71-52.2N	009-42.7W	17	21.6	2500
39	71-27.0N	010-47.1W	18	02.4	1800
40*	71-21.4N	009-04.7W	18	08.3	2220
41	71-44.8N	007-49.0W	18	17.5	2000
42	72-08.1N	006-38.5W	19	00.1	2880
43	72-31.0N	005-26.1W	19	05.4	2640
44	72-52.8N	003-57.3W	19	14.2	2050
45	73-20.0N	003-01.4W	19	19.1	3000
46	72-46.5N	003-01.6W	19	23.9	2790
47	71-54.4N	004-14.5W	20	06.8	1070
48*	70-59.1N	006-31.1W	20	14.9	3610

* Deep Cast (>1000 dbar)

pre-cruise calibration. A post-cruise calibration will also be conducted by the ODF. These two calibrations will comprise the temperature and pressure corrections. While at sea David Muus, a member of the ODF staff, ran salinity and dissolved oxygen samples for us. A 12-place rosette sampler was provided by the ODF as well as three racks of low-temperature (-2°C to +2°C) reversing thermometers. Water samples were collected at all but two stations. In order to further enhance the intercomparison of data among GSP investigators all salinities were run against a common lot of oceanographic standard water (Wormley batch number 108).

The CTD data acquisition program is designed to permit 8616 data bytes to be collected, evenly spaced over the depth range selected prior to lowering. Hence, for our nominal 1000 m depth casts, approximately nine observations would be collected per meter. The instrument was lowered at a nearly constant rate of 60 m min^{-1}, varying with the roll of the ship. Deep casts were done in two segments, 0 to 1000 m and 1000 m to 3000 m. The sampling rate for the deep segments was 4.3 observations per meter.

An instrument calibration report will be provided by the ODF. A preliminary analysis indicates a slight drift with time in the conductivity data and a substantial dependence on pressure for the conductivity cell for depths greater than 1000 m leading to salinity differences ranging from 0.062 to 0.104 PSU between bottle and CTD measurements at 3000 m. This pressure dependence is thought to arise due to a fault in the cell, whose effect varied from cast to cast. Thus appropriate corrections had to be applied to each deep conductivity profile using a second order regression equation. The rms error over the 1000 m to 3000m depth range varied from 0.0012 to 0.0016. The errors from the surface to 1000m were more coherent and the salinities were corrected by a single regression equation to a rms accuracy of approximately 0.0035 PSU.

V. NARRATIVE

The scientific party departed CONUS for Tromso, Norway on 1 September 1989 and arrived around 1700 on 2 September. On 3 and 4 September we unpacked, secured and tested all equipment. The ship was originally scheduled to sail on 5 September but at the request of the Chief Scientist the departure date was delayed one day. This was necessary in order to obtain the acoustic moorings retrieved by the Norwegian ice breaker ANDERNESS which was delayed in returning to port with the mooring components. We departed Tromso around 2200 6 September. After leaving the fjord we headed for the calibration site at 71°N, 4°E. Our westward progress was slow (6 to 8 knots) due to pounding of the vessel in rough seas. Throughout the cruise east-west traverses had to be accomplished by tacking north and south of the desired headings as the seas were mostly from the north. Thus, the ship was initially forced to head predominantly northward, causing us to bypass the calibration site.

During the afternoon of 7 September we made Station 999 which was a lowering of the ship's (NAVOCEANO) CTD followed by the NPS CTD. This was done to provide a calibration for the NAVOCEANO instrument in the event it had to be used in place of the NPS CTD. A visual inspection of the temperature and salinity traces indicated little or no difference between instruments.

We arrived at the first mooring site around 1000 on 9 September. The mooring was placed in 1805 m of water (corrected for speed of sound, about 50 m less than recorded) near the southern end of the Greenland Fracture Zone. See Table 3 and a report by Gascard and Richez (1989) for more details concerning the moorings.

We continued westward towards the ice edge. Station 2 was the first of five deep CTD casts. This station was made to characterize the properties of the EBDW. To make a deep station took about 3 to 4 hours.

Mooring 2 was inserted around 2320Z on 9 September in 1880 m of water at a location near the northern end of the Greenland Fracture Zone.

After further westward progress we encountered the ice edge around 1400Z on 10 September. Station 4 was made about 3 km seaward of the ice edge. The day was bright and sunny (the only time on the cruise) and the seas calm. The ice margin looked to be very compact with many ridges in view.

Table 3. Acoustic Mooring Characteristics

Mooring # 1
- Location: 75° 11.500'N, 0011o 35.057'E
- Date inserted: 1225Z 9 September 1989
- Water depth: 1805 m (corrected)
- ALS # 17, release # 44

Mooring # 2
- Location: 76° 01.713'N, 000° 23.019'W
- Date inserted: 2320Z 10 September 1989
- Water depth: 1880 m (corrected)
- ALS # 19, release # 41

Mooring # 3
- Location: 72° 20.944'N, 011° 33.560'W
- Date inserted: 0011Z 14 September 1989
- Water depth: 1270 m (corected)
- ALS # 13, release # 183

Mooring # 4
- Location: 72° 53.188'N, 003° 54.239'W
- Date inserted: 1334Z 19 September 1989
- Water depth: 2050 m (corrected)
- ALS # 15, release # 45

Note: Each mooring has a radio beacon transmitting on 160.785 MHz (Channel D)

We attempted to make a line of stations parallel to the ice edge but about 35 km seaward of it. However, fog set in and we spent the night steaming eastward to clear an ice edge protrusion. Due to time constraints and poor knowledge of the ice edge location we abandoned the proposed line of stations along the ice edge.

As shown in Figure 1, a total of five southwest/northeast tending hydrographic lines were made, labeled as transects A through E. The second line was extended farther northward than originally planned in order to re-visit the site of the first acoustic mooring. Since an incorrect acoustic interrogation code was used to verify the proper functioning of the mooring's acoustic release upon implantation, a second pass overhead the location was deemed necessary.

On 13 September we were joined by a Soviet research vessel which sailed around the BARTLETT before departing. She did not respond to our attempts to communicate with her.

Mooring three was inserted near midnight 14 September in 1270 m of water on a shallow promontory near 72°N just seaward of the shelf break. On 19 September the last mooring was installed. This was the deepest mooring, 2050 m, placed on one of the rises of the Mohns Ridge.

On 20 September at 1800Z we finished Station 48, a deep cast and regrettably our final station. The seas were quite high (12 to 14 foot swells) due to the presence of a stationary low pressure center, requiring the ship to tack toward our intended final station, the calibration site, at a significantly reduced speed of advance. The position of this station was moved to 71°N, 1°E to comply with a message from the COMSUBLANT representative in Northwood, England restricting any CTD operations east of 1°E. By noon on 21 September at least 16 hours were required to transit to the calibration site, barely sufficient time to make the deep station and return to Trondheim on schedule. In addition, the seas at that time were too high to permit making CTD observations. Hence, we abandoned the effort to make the calibration site and headed the ship for Trondheim. This decision was heavily influenced by the fact that the ship was using up a limited supply of fuel oil filters at a rapid rate due to the extreme pitching of the vessel and could have possibly been without the use of its main engines if the eastward heading was maintained.

V. RESULTS

1. Water Masses of the Jan Mayen Current

It is possible to map the path of the JMC by tracing its low temperature, low salinity surface signature (Figures 3 and 4). Such is not always the case as demonstrated by the climatological average data of Koltermann and Machoczek (1985) which demonstrate

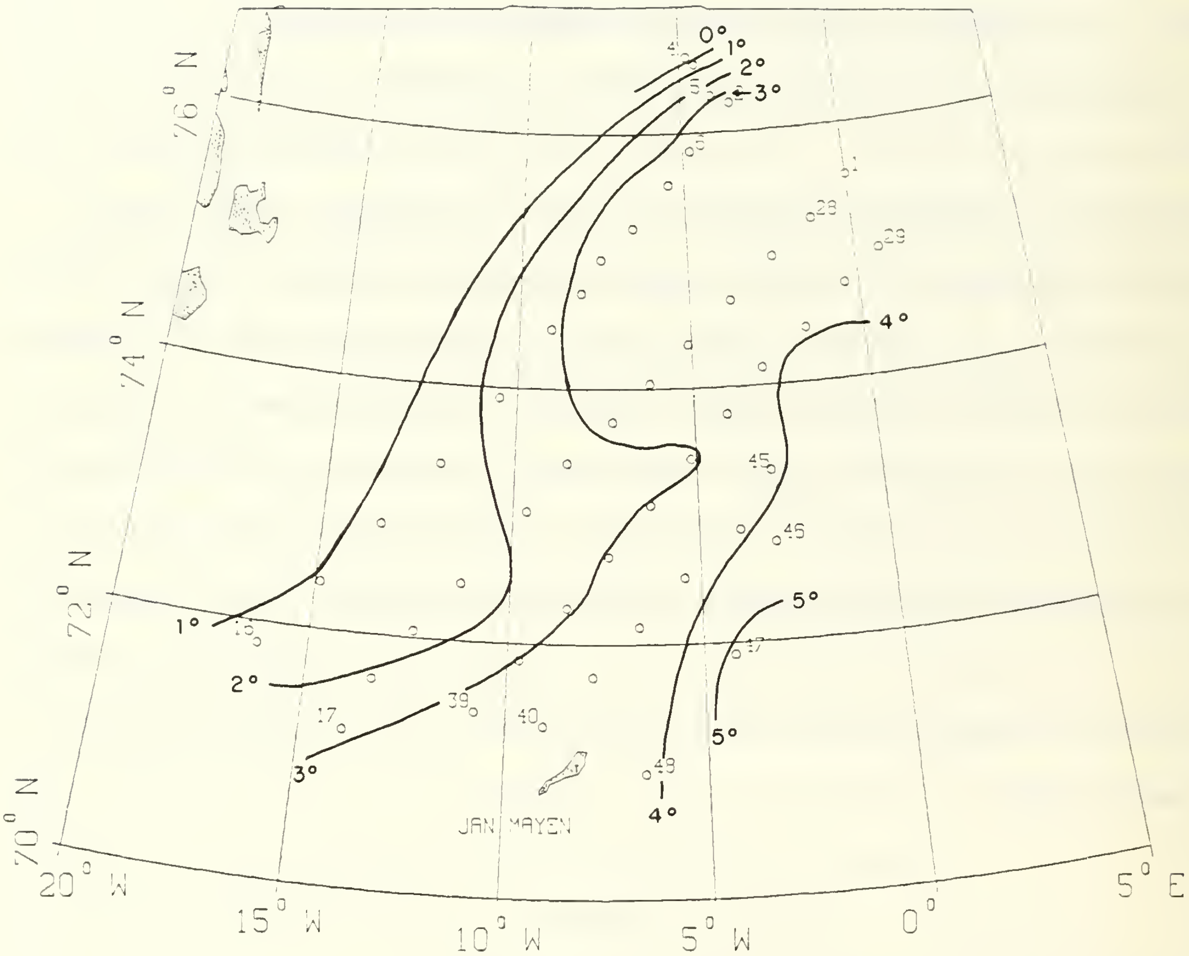

Figure 3. Contours of surface temperature (°C) illustrate the path of the Jan Mayen Current.

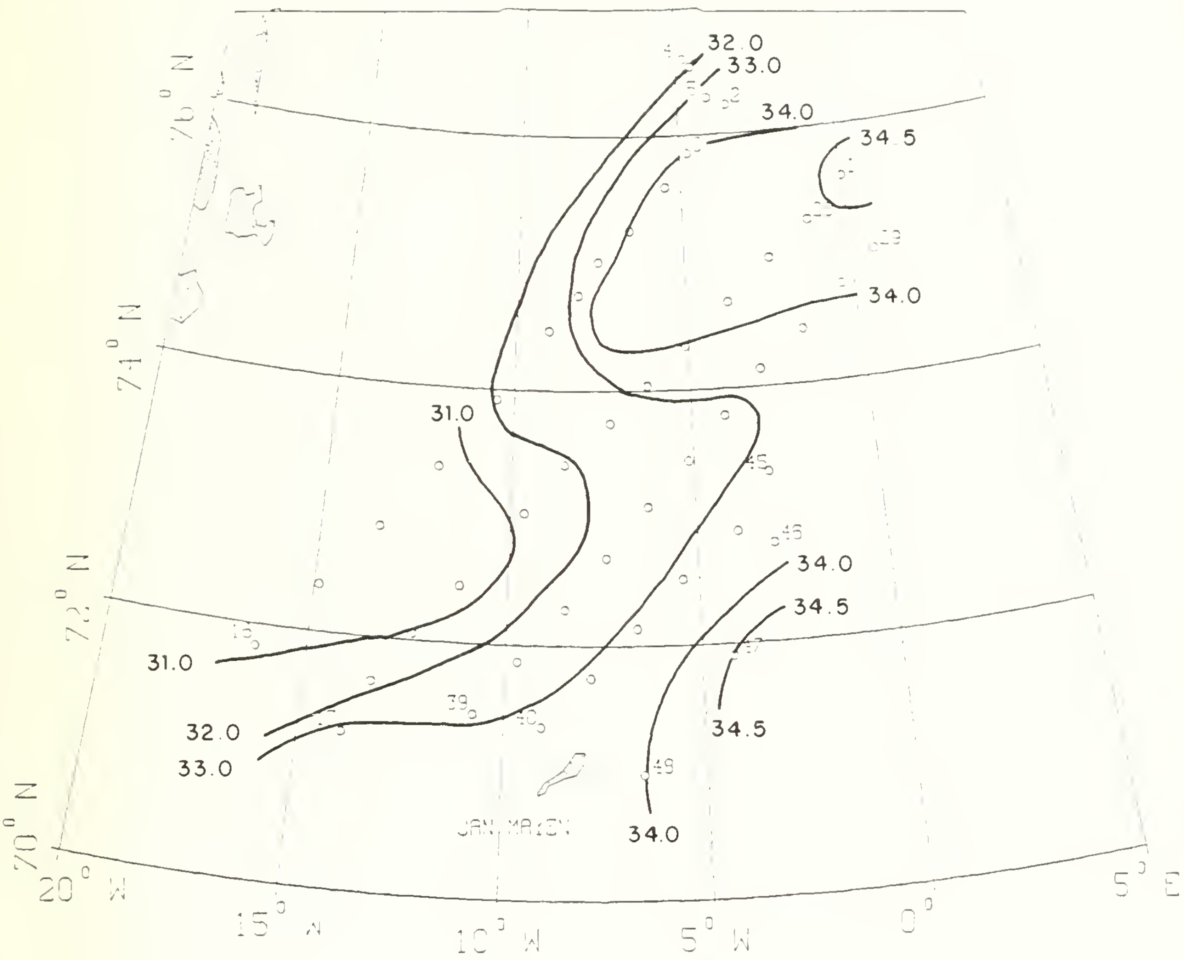

Figure 4. The path of the Jan Mayen Current is clearly observed by the northeast projection of a low salinity tongue originating in the East Greenland Current.

a strong signal only in salinity during summer. The summer 1989 surface contour patterns are similar in both temperature and salinity to those derived from the IGY 58 summer data. However, significant differences are noted between the two data sets. The JMC in summer 1989 was centered near 73°N, approximately 75 km south of its track in 1958. In 1989 the surface temperature in the area of the JMC ranged from <0°C to 3°C and surface salinities from <31.0 to 33.0 whereas during 1958 summer temperatures were approximately 1°C warmer and salinities were markedly higher ranging from 34.0 to 34.9 (Deitrich, 1969).

The flow of the JMC can also be tracked from its intermediate water properties (Figures 5 and 6). Jan Mayen Intermediate Water (JMIW) has been defined as having temperatures from 0° to 0.5°C and salinities >34.9 (Hopkins, 1988), though we observed temperatures in the core of the current in excess of 1.5°C. The IGY 58 summer data show similar eastward protrusions of warm, saline intermediate water, though less well defined due to the poorer spatial resolution of bottle data, with similar ranges of temperature and salinity (Deitrich, 1969).

A small wave-like feature in the temperature and salinity contours of the EGC intermediate water appears near Station 6 (Figures 5 and 6), perhaps generated by interaction with the 2000 m isobath which projects seaward at this point. This feature was not detected in the IGY 58 data probably due to the coarser

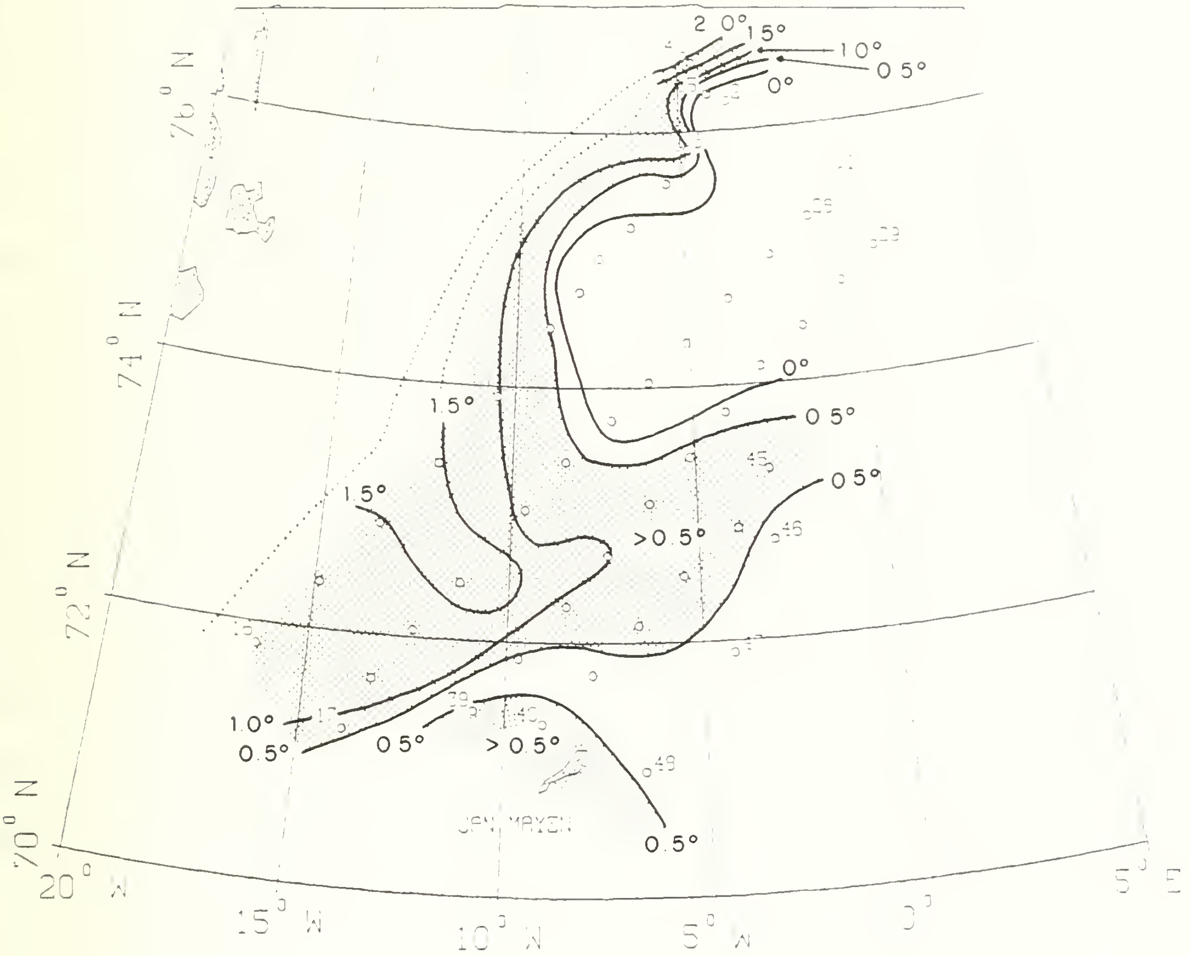

Figure 5. Contours of the maximum subsurface temperature in the water column (°C). The shaded areas illustrate the path of the intermediate waters of the East Greenland Current and Jan Mayen Current.

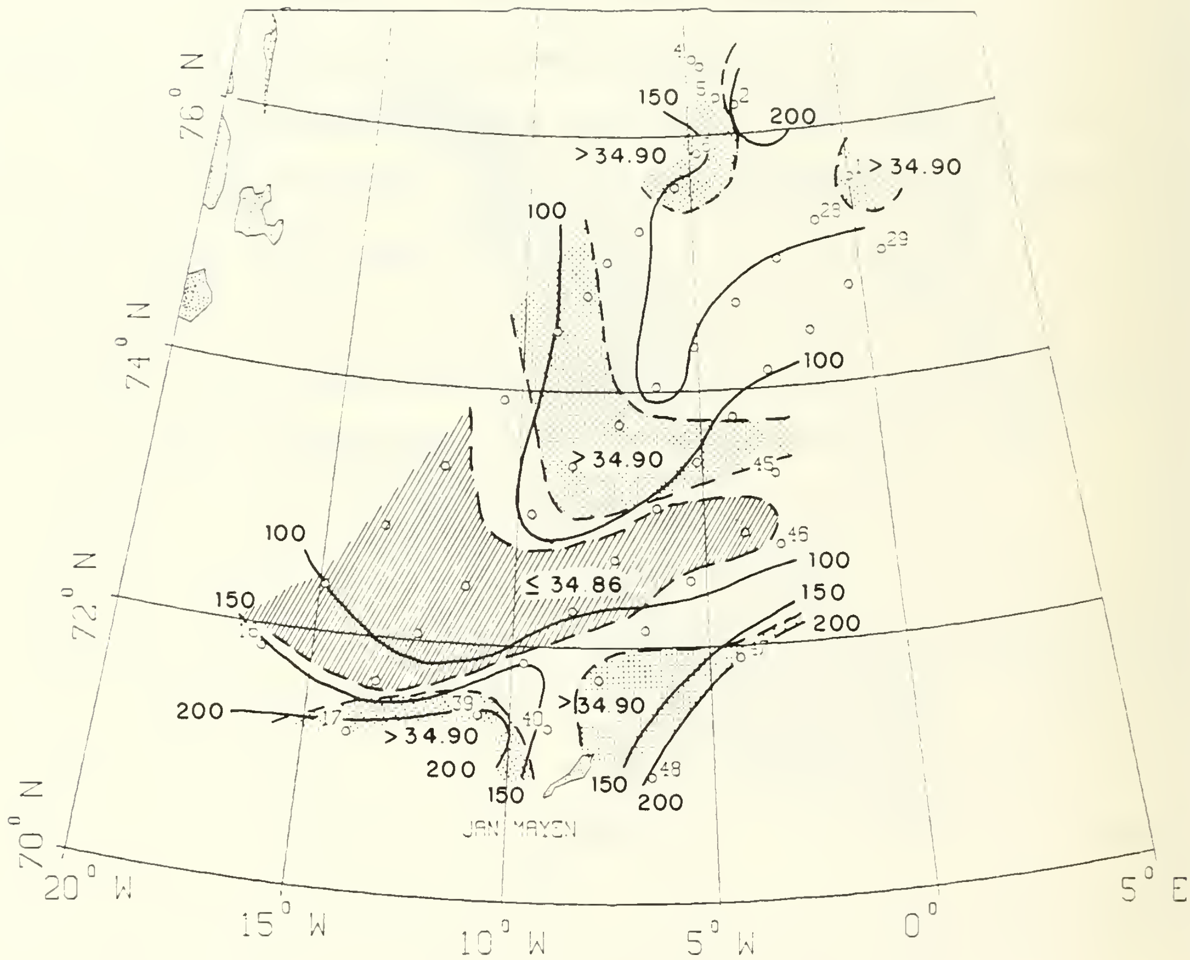

Figure 6. Contours of the depth (meters) of the subsurface temperature maximum (solid line) and salinity (dashed line) at the temperature maximum. The Jan Mayen Current is observed by the low salinity (<34.86 PSU) stippled area and shallow intermediate water depths.

sampling interval in this area. The preceeding figures illustrate that the main core of the JMC departs the EGC southward of Station 10, apparently due to bathymetric steering as it is initially aligned with the Jan Mayen Fracture Zone (JMFZ) (Figure 2).

Transect A (Figure 7) starts in the seaward fringe of the EGC, judging from the high temperatures of the intermediate water near 50-100 m depth. The transect then passes into the cold waters of the central gyre after Station 7 and reenters the warmer EGC at Station 11. These warm, saline waters exhibit the characteristics of the Atlantic Intermediate Water (AIW) found in the Return Atlantic Current, the warm water component of the EGC (Paquette et al., 1985; Bourke et al., 1987; Hopkins, 1988). The extremely high temperature and salinity maximum of the intermediate water near Stations 3 and 4 (Figures 5 and 6) also show evidence of AIW in the EGC. At Station 11 (Figure 7) a rapid increase in depth of the 0°C isotherm marks the point where the JMC initially turns eastward from the EGC and AIW becomes JMIW.

The 0°C isotherm, steeply sloping through the first 500 meters, in Transects B and C (Figures 8 and 9) becomes the boundary between the intermediate waters of the JMC and both the arctic waters within the main gyre to the north and the deep waters approximately 500 m below. In these figures the

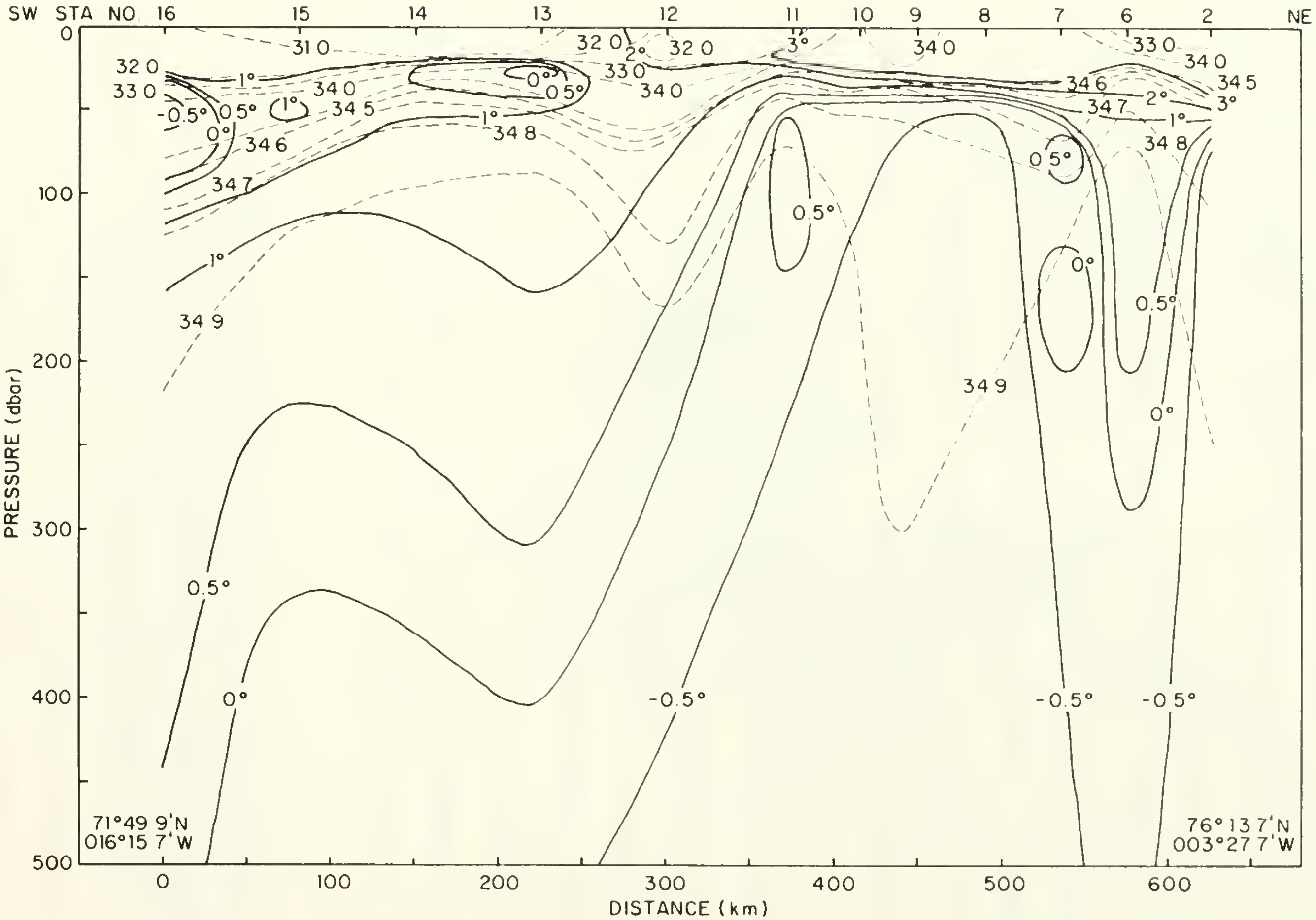

Figure 7. Transect A, a vertical temperature (solid line) and salinity (dashed line) cross-section approximately 50 km seaward of the ice edge and parallel to the East Greenland Current. The axis of the Jan Mayen Current is observed by the downbowing of isotherms at Station 13.

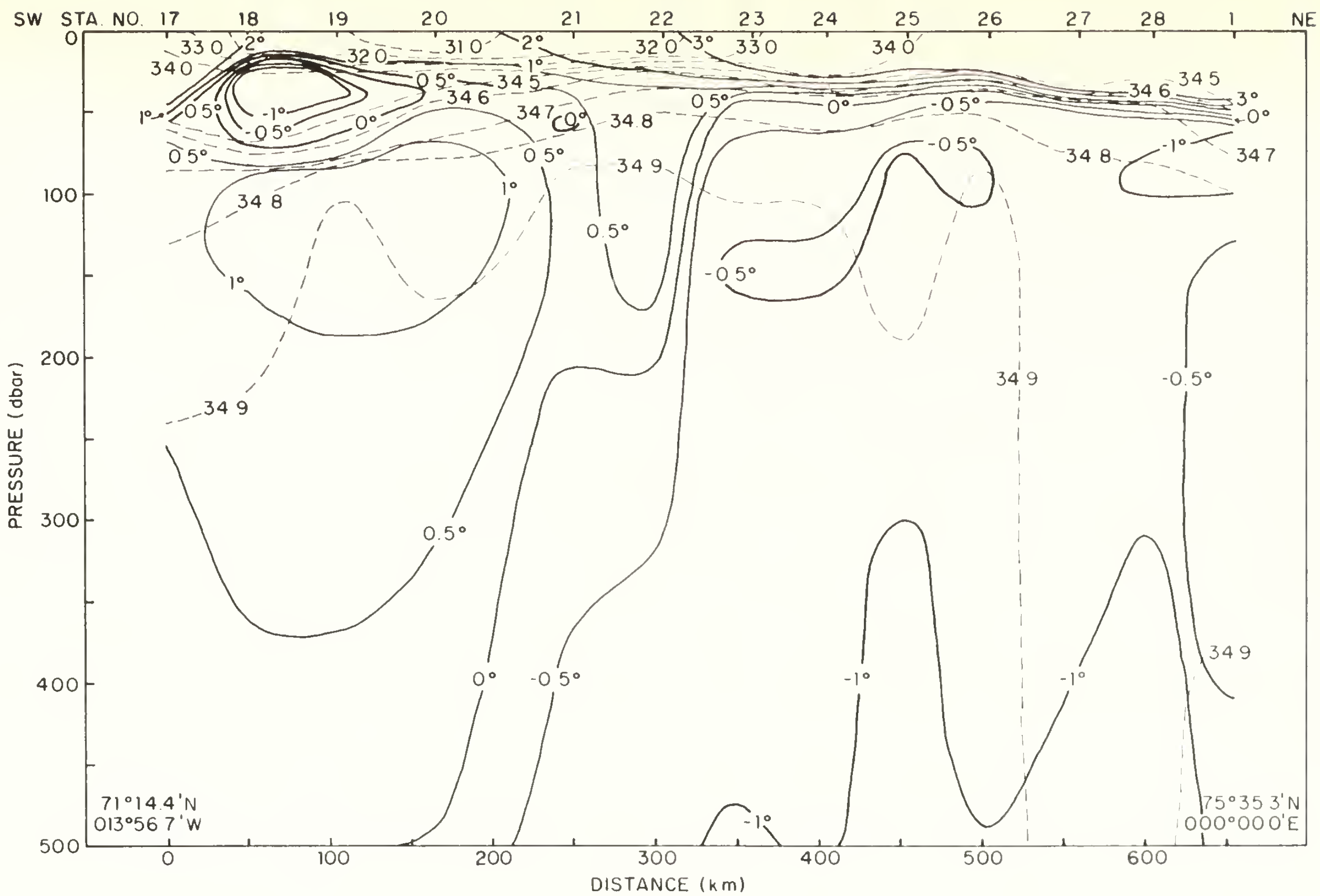

Figure 8. Transect B. The Jan Mayen Current is observed by the presence of cold, fresh polar water near Stations 18 and 19 and warm, salty intermediate water below 100 m depth near Stations 18, 19, and 20.

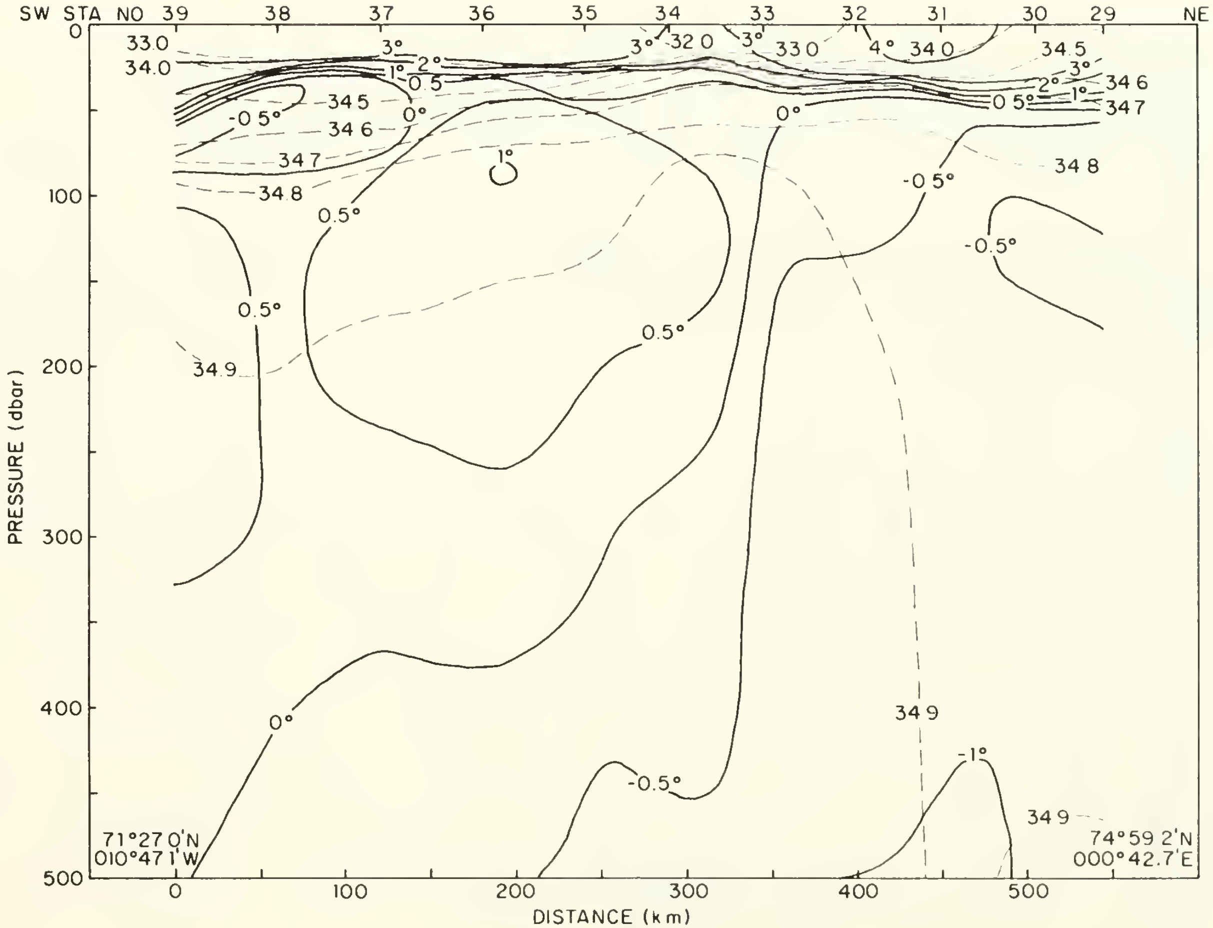

Figure 9. Transect C, 220 km seaward of the ice edge, shows cooling of the Jan Mayen Intermediate Water. Only a small portion centered near Station 36 remains above 1°C.

subsurface and intermediate water structure of the JMC is observed to consist of a cold, fresh filament of Jan Mayen Polar Water (JMPW) (temperature <-0.5°C, salinity <34.6) enclosed by a secondary 0°C isotherm over a warm, salty filament of JMIW enclosed by a secondary 0.5°C isotherm. The exact manner by which these filaments issue from the water masses in Transect A (Figure 7) in the EGC is not readily apparent at this early stage of data analysis. Figures 8 and 9, like Figure 7, also illustrate that northward of the JMC and seaward of the shelf break, the surface and intermediate waters take on the characteristic properties of Greenland Sea Polar Water (GSPW) and Intermediate Water (GSIW) (Hopkins, 1988). Isotherms and isohalines are bowed upward in the well-recognized doming of cold water within the cyclonic Greenland Sea gyre.

Transects C,D, and E (Figures 9, 10 and 11) show that the warm core of the JMIW cools to less than 1°C and diminishes in size with continued eastward propagation while the cold core of JMPW persists with little change in size. Transects C and D show a separate warm core south of Stations 38 and 41, respectively, that perhaps indicates a secondary source of warm, salty water from the south of Jan Mayen Island. This southern core shares similar water mass characteristics with the main core having waters warmer than 0.5°C. It is not clear whether its source is a second filament of AIW from the EGC or perhaps a meander in the North Atlantic Current which passes north of Jan Mayen Island

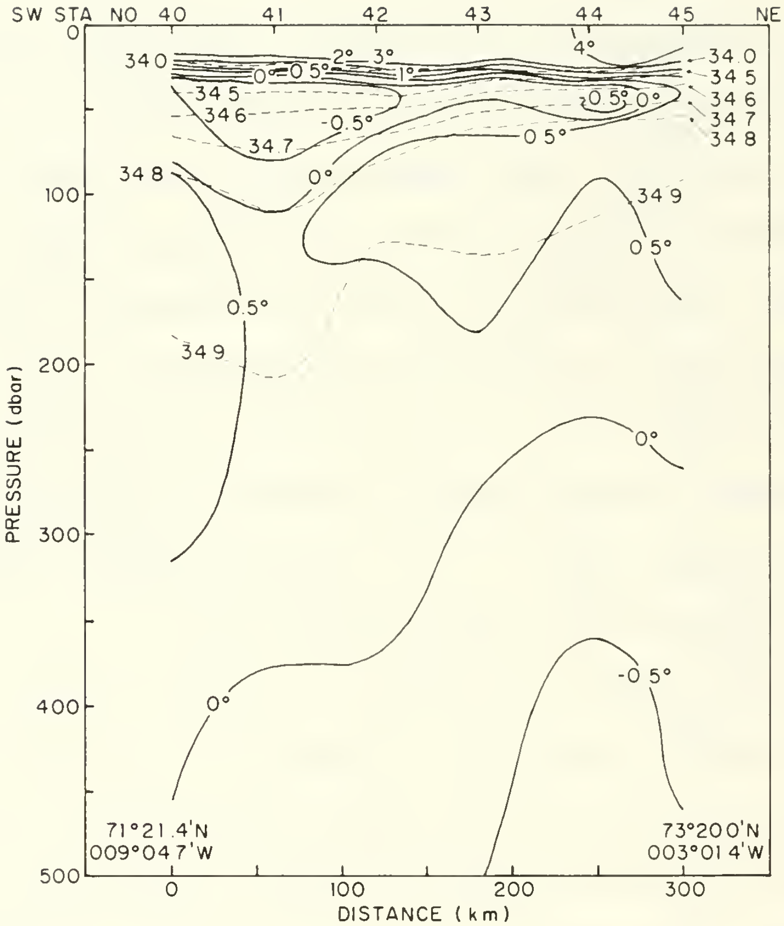

Figure 10. Transect D. Note that the polar waters and intermediate waters of the Jan Mayen Current are becoming more and more laterally displaced. Compare with Figures 8 and 9.

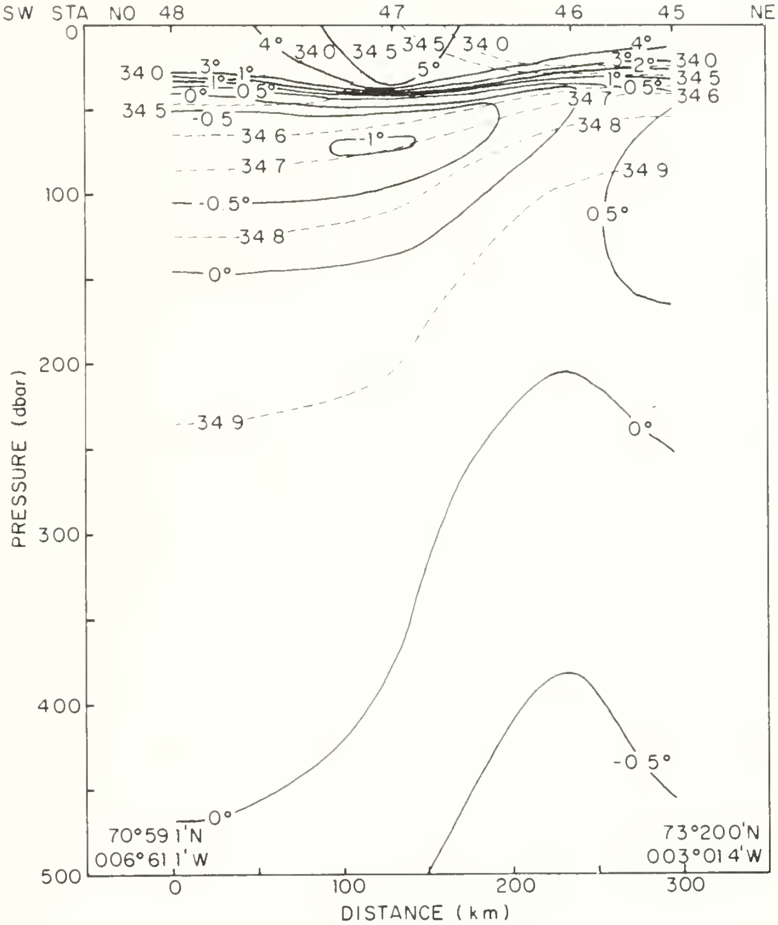

Figure 11. Transect E, 330 km from the ice edge. Little is seen of the Jan Mayen Current either in the polar water or the intermediate water.

(Hopkins, 1988). Evidence of warm core cooling and shrinking as well as a separate warm core is also apparent in the contours of maximum temperature in the intermediate water (T_{max}) and salinity at T_{max} (Figures 5and 6, respectively).

2. Deep Waters of the Greenland and Norwegian Seas

Five CTD stations were made which extended to near bottom in deep water, generally 3000 m or deeper, to monitor the deep water properties of the Greenland and Norwegian Seas. Three stations (2, 11, and 21) were in the Greenland Basin, south of the Greenland Fracture Zone (GFZ). Station 2 is in the north of the basin, Station 11 near its center, and Station 21 in the south central part of the basin (Figure 2). Temperature and salinity data from these three stations show a remarkable uniformity at deeper depths with a slight latitudinal change (Table 4). Temperatures below 2500 m become increasingly colder towards the south while deep salinities remain essentially unchanged (although a slight freshening towards the south is indicated). This latitudinal change in water properties is precisely what might be expected if GSDW is modified by mixing with warmer and saltier EBDW in the northern reaches of the Greenland Sea as postulated by Swift and Koltermann (1988). The temperature and salinity values from these three stations at 3000 m depth are very similar to those discribed as typical of GSDW by Aagaard et al. (1985), Swift and Koltermann (1988), and Hopkins (1988)

Table 4. Deep Water Properties of the Greenland and Norwegian Seas

*Potential Temperature (°C)

Pressure (dbar)	2000-2100	2200-2250	2500-2550	2700	2850-3000	3500
Sta. No.						
2	-1.133	-1.143	-1.175	-1.188	-1.211	
11	-1.136	-1.152	-1.177	-1.188	-1.216	
21	-1.113	-1.139	-1.183	-1.204	-1.215	
40	-1.094	-1.139				
48	-1.018	-1.034	-1.055	-1.061	-1.067	-1.068
Cal Site	-0.930	-0.978	-1.035	-1.040	-1.045	

**Salinity (PSU)

2	34.900	34.899	34.898	34.897	34.896	
11	34.903	34.901	34.897	34.895	34.896	
21	34.901	34.900	34.896	34.896	34.895	
40	34.905	34.902				
48	34.907	34.907	34.906	34.905	34.906	34.906
Cal Site	34.908	34.908	34.907	34.907	34.908	

*Corrected CTD temperatures at depth of bottle trip
**Salinities determined from water samples run on autosal

(Table 5).

To monitor the possible exhange of deep water between the Greenland Sea and the Norwegian Sea, two deep stations were made in the deep trough of the JMFZ, just to the north of Jan Mayen. Station 40, located on the Greenland Sea side of the Mohns Ridge and northwest of Jan Mayen, extended to 2250 m, just above the bottom. Station 48 was made 111 km to the east of Station 40 in a deep depression in the JMFZ. This station was on the east side of the Mohns Ridge, i.e., in the Norwegian Sea (Figure 1).

The temperature-salinity characteristics of Station 40 at 2250 m are similar to those of Stations 2,11, and 21 from the central Greenland Basin. At this depth the slight warming and salt increase of the more southerly stations is most likely an effect of the JMC. However, the water properties near the bottom of the trough of the JMFZ leave little doubt that this water is of Greenland Sea origin.

The deep water properties at Station 48 are quite different from those of Station 40 and the three stations farther north, being significantly warmer and saltier. A comparison with Table 5 indicates that here, on the extreme western periphery of the Norwegian Sea, the deep water has nearly the same temperature-salinity properties as that in the central Norwegian Sea, the latter being slightly warmer and saltier.

Since no stations were occupied in the central Norwegian Sea during the BARTLETT cruise, deep water temperature and salinity properties from this region can be ascertained from the data

Table 5. Historical Deep Water Properties from the Norwegian and Greenland Seas

Greenland Sea Deep Water

Reference	Temperature (°C)	Salinity (PSU)	Remarks
1	T < -1	34.85 - 34.95	Greenland Basin
2	T < -1	34.88 - 34.90	Cntrl Grnlnd Sea
3	-1.26 < O < -1.29	34.889 - 34.892	range > 2000 m
4	O = -1.28	34.89	
5	O = -1.242	34.895	mean below 2000 m
6	O = -1.25	34.895	mean below 2000 m

Norwegian Sea Deep Water

Reference	Temperature (°C)	Salinity (PSU)	Remarks
2	T < -0.4	34.90 - 34.94	
3	-0.93 < O < -1.06	34.908 - 34.911	range > 2000 m
4	O = -1.08	34.91	
5	O = -1.048	34.910	
6	O = -1.05	34.91	mean below 2500 m

Ref. 1: Carmack and Aagaard, 1973
Ref. 2: Swift and Aagaard, 1981
Ref. 3: Swift et al., 1983
Ref. 4: Aagaard et al., 1985
Ref. 5: Swift and Koltermann, 1988
Ref. 6: Hopkins, 1988

acquired by the HAAKON MOSBY two months earlier (Foldvik, 1989) at the GSP common calibration site. The HAAKON MOSBY CTD was also calibrated at the ODF/SIO and salinities determined from the same batch of Wormley oceanographic standard water as employed on the BARTLETT cruise, thus ensuring reliable intercomparison between CTD systems.

As noted above, the deep water of Station 48 is slightly colder (0.02°C) and fresher (0.002 PSU) than the NSDW resident in the central Norwegian Basin. This relationship of properties was also noted by Swift and Koltermann (1988) who termed the deep waters just east of Jan Mayen "new NSDW" in contrast to the "old NSDW" of the Lofoten Basin. In their thinking the new NSDW represents waters which have recently been formed by a mixture of GSDW and EBDW and enters the Norwegian Sea primarily through the deep channel of the JMFZ.

The rather abrupt change in deep water properties over the 111 km distance between Stations 40 and 48, however, would argue for a more limited exchange of deep waters through this channel. Since no obvious topographic rise or sill is evident within the channel as viewed on recent bathymetric charts (Perry et al., 1980; Perry and Fleming, 1986), a dynamic constraint may be present in the channel which inhibits an active interchange between the two basins. The presence of dilute NSDW observed at Station 48 indicates that the interchange through the JMFZ is a slow, diffusive process rather than active, advective one. The interchange of waters is characterized by two-part mixing between pure GSDW at Station 40 and pure NSDW at the intercalibration site, there being no evidence of EBDW on the west side of the trough. Small episodic flows of an admixture of GSDW and EBDW through the JMFZ, however, cannot be ruled out. If NSDW is derived from such a mixing process as postulated by Swift and Koltermann (1988), it is more likely to take place farther north in the Greenland Sea, perhaps in the Boreas Basin where EBDW is more prevalent, subsequently entering the Norwegian Sea through fractures in the mid-ocean ridge.

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VII. REFERENCES

Aagaard, K., J. H. Swift, and E. C. Carmack, Thermohaline circulation in the Arctic Mediterranean Seas, J. Geophys. Res., 90(C3), 4833-4846, 1985.

Bourke, R. H., J. L. Newton, R. G. Paquette, and M. D. Tunnicliffe, Circulation and water masses of the East Greenland Shelf, J. Geophys. Res., 90(C7), 6729-6740, 1987.

Carmack, E. C., and K. Aagaard, On the deep water of the Greenland Sea, Deep-Sea Res., 20, 687-715, 1973.

Dietrich, G., Atlas of the hydrography of the northern North Atlantic, 140 pp., Int. Counc. Explor. Sea, Copenhagen, 1969.

Foldvik, A., HAAKON MOSBY June 1989 Greenland Sea data report (in prep).

Gascard, J. C., and C. Richez, ARCTEMIZ 89 mission report, 17 August-26 September 1989, Laboratoire D'Oceanographie Dynamique et de Climatologie, Paris, LODYC 89/05, October 1989.

Hopkins, T. S., The GIN Sea-Review of physical oceanography and literature from 1972, SACLANTCEN Rpt. SR-124, SACLANT Undersea Research Center, La Spezia, Italy, 190 pp., 1988.

Koltermamm, K. P., and Machoczek, D. On the climatological mean state distribution of temperature and salinity in the Greenland Sea, ICES C. M., C: 39, 1985 (Unpublished documemt).

Paquette, R. G., R. H. Bourke, J. L. Newton, and W. F. Perdue, The East Greenland Polar Front in autumn, J. Geophys. Res., 90(C3), 4866-4882, 1985.

Perry, R. K., H. S. Fleming, N. Z. Cherkis, R. H Feden, and P. R. Vogt, Bathymetry of the Norwegian-Greenland and western Barents Seas, chart, Acoust. Div., Environ. Sci. Branch, U. S. Nav. Res. Lab., Washington, D. C., 1980.

Perry, R K., and H. S. Fleming, Bathymetry of the Arctic Ocean, chart, Acoust. Div., Environ. Sci. Branch, U. S. Nav. Res. Lab., Washington, D. C., 1986.

Swift, J. H., and K. Aagaard, Seasonal transitions and water mass formation in the Iceland and Greenland Seas, Deep-Sea Res., 28A(10), 1107-1129, 1981.

Swift, J. H., T. Takahashi, and H. D. Livingston, The contribution of the Greenland and Barents Seas to the deep water of the Arctic Ocean, J. Geophys. Res., 88(C10), 5981-5986, 1983.

Swift, J. H., and K. P. Koltermann, The origin of Norwegian Sea deep water, J. Geophys. Res., 93(C4), 3563-3569, 1988.

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